

# The BABAR resonance as a four-quark meson\*

K. Terasaki

Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

(Dated: May 20, 2003)

A possible assignment of the new resonance observed at the  $B$  factories to a four-quark meson,  $\hat{F}_I^+ \sim \{[cu][\bar{s}\bar{u}] - [cd][\bar{s}\bar{d}]\}$ , is proposed and two-body decays of four-quark mesons through  $I$ -spin conserving strong interactions are studied. It is expected that some of them can be observed as narrow resonances. Implication of existence of four-quark mesons in hadronic weak interactions is also discussed.

Recently a scalar  $D_s^+\pi^0$  resonance with a mass  $\simeq 2.32$  GeV and a width  $\sim 10$  MeV has been observed at the  $B$  factories [1]. The above values of the mass and the width have been obtained from Gaussian fits, and then it has been concluded that the intrinsic width is equal to or narrower than  $\sim 10$  MeV. While it has been interpreted as an ordinary  $c\bar{s}$  state such as the chiral partner of  $D_s^+$  [2] or the excited  $c\bar{s}$  state [3], their predicted mass values are still in controversy [4]. In addition, possible assignments to exotic hadron states such as a  $(DK)$  molecule [5] (or atom [6]), an isospin ( $I$ ) singlet four-quark meson [7], a mixed scalar state of a  $c\bar{s}$  and an iso-singlet four-quark meson [8], etc. have also been proposed. In all the above proposals, however, the dominant decay of the new resonance into the  $D_s^+\pi^0$  final state proceeds through  $I$ -spin non-conserving interactions since it has been assigned to an iso-singlet state, and therefore it should be extremely narrow. In this talk, we will propose another possible assignment to a singly charged component of iso-triplet scalar four-quark mesons in contrast with the above proposals.

Four-quark mesons,  $\{qq\bar{q}\bar{q}\}$ , can be classified into four types [9],

$$\{qq\bar{q}\bar{q}\} = [qq][\bar{q}\bar{q}] \oplus (qq)(\bar{q}\bar{q}) \oplus \{[qq](\bar{q}\bar{q}) \pm (qq)[\bar{q}\bar{q}]\}, \quad (1)$$

where parentheses and square brackets denote symmetry and anti-symmetry, respectively. Only the  $[qq][\bar{q}\bar{q}]$  and  $(qq)(\bar{q}\bar{q})$  can have  $J^{P(C)} = 0^{+(+)}$  at the lowest level. Each of them is again classified into two classes since there exist two different configurations to produce color singlet scalar states, i.e.,  $\mathbf{6} \times \bar{\mathbf{6}}$  and  $\bar{\mathbf{3}} \times \mathbf{3}$  of color  $SU_c(3)$ . However, these two can mix with each other, so that they are classified into heavier and lighter ones. The former is dominated by the  $\mathbf{6} \times \bar{\mathbf{6}}$  of  $SU_c(3)$  while the latter by the  $\bar{\mathbf{3}} \times \mathbf{3}$  since the force between two quarks is repulsive when they form a  $\mathbf{6}$  of  $SU_c(3)$  while attractive when  $\bar{\mathbf{3}}$  [10]. We discriminate these two by putting  $*$  on the former in accordance with Ref. [9] in which the four-quark mesons were studied within the framework of  $q = u, d$  and  $s$ . It can be extended straightforwardly to the one including  $q = u, d, s$  and  $c$  [11].

In this talk, we concentrate on the  $[cq][\bar{q}\bar{q}]$  mesons (with  $q = u, d, s$ ). We now assign the new resonance to  $\hat{F}_I^+ \sim \{[cu][\bar{s}\bar{u}] - [cd][\bar{s}\bar{d}]\}$  and estimate the masses of the lighter class of the  $[cq][\bar{q}\bar{q}]$  mesons using the simple quark counting and taking  $\Delta m_s = m_s - m_n \simeq 0.1$  GeV, ( $n = u, d$ ), at  $\sim 2$  GeV scale and the measured  $m_{\hat{F}_I} = 2.32$  GeV as the input data [12]. To estimate the mass values of the heavier class of  $[cq][\bar{q}\bar{q}]$  mesons, we use  $\Delta m_c = m_c - m_n \simeq 1.5$  GeV and  $m_{\hat{\kappa}^*} \simeq 1.6$  GeV [9] as the input data. Their estimated mass values are listed in **TABLE 1**.

**TABLE 1.** Ideally mixed scalar  $[cq][\bar{q}\bar{q}]$  mesons (with  $q = u, d, s$ ), where  $S$  and  $I$  denote the strangeness and the isospin.

$S$	$I = 1$	$I = \frac{1}{2}$	$I = 0$	Mass(GeV)
1	$\hat{F}_I$		$\hat{F}_0$	2.32(†)
	$\hat{F}_I^*$		$\hat{F}_0^*$	(3.1)
0		$\hat{D}$		2.22
		$\hat{D}^*$		(3.0)
		$\hat{D}^s$		2.42
		$\hat{D}^{s*}$		(3.2)
-1			$\hat{E}^0$	2.32
			$\hat{E}^{0*}$	(3.1)

(†) : Input data

\* Talk given at Hadron2003, the X-th International Conference on Hadron spectroscopy, August 31 – September 6, 2003, Aschaffenburg, Germany

As seen in **TABLE 1**, the four-quark mesons with \* have large masses enough to decay into two vector mesons in addition to two pseudoscalar mesons, so that they will be broad. On the contrary, the estimated masses of  $[cq][\bar{q}\bar{q}]$  without \* are near (or lower than) the thresholds of two body decays through  $I$ -spin conserving strong interactions, so that their phase space volumes are small even if kinematically allowed. Besides, it is seen [13], from the crossing matrices for color and spin in Ref. [9], that the wavefunction overlapping between the scalar  $[qq][\bar{q}\bar{q}]$  meson and the two pseudoscalar  $q\bar{q}$  meson state is small since the former is dominated by the  $\bar{\mathbf{3}} \times \mathbf{3}$  of color  $SU_c(3)$  and the  $\mathbf{1} \times \mathbf{1}$  of spin  $SU(2)$ . Therefore, some of them can decay through  $I$ -spin conserving interactions but their rates will be small and they can be observed as narrow resonances such as the new resonance. Since some of them are not massive enough to decay into two pseudoscalar mesons through  $I$ -spin conserving interactions, their dominant decays may be  $I$ -spin non-conserving ones (unless their masses are higher than the expected ones).

The  $\hat{F}_I$  mesons form an iso-triplet,  $\hat{F}_I^{++}$ ,  $\hat{F}_I^+$  and  $\hat{F}_I^0$ , where the  $I$ -spin symmetry is always assumed in this talk unless we note. Then all of them can have the same type of kinematically allowed decays,  $\hat{F}_I \rightarrow D_s^+ \pi$ , with different charge states. The  $\hat{D}$  and  $\hat{D}^s$  form two independent iso-doublets. The  $\hat{D}$  can decay into  $D\pi$  final states and the kinematical condition is similar to the one in the decay,  $\hat{F}_I \rightarrow D_s^+ \pi$ , as long as the mass value of  $\hat{D}$  in **TABLE 1** is taken. The dominant decay of  $\hat{D}^s$  which contains an  $s\bar{s}$  pair would be  $\hat{D}^s \rightarrow D\eta^s \rightarrow D\eta$ . Because of  $m_{\hat{D}^s} \simeq m_D + m_\eta$ , however, it is not clear if such a decay is allowed kinematically, as long as the value of  $m_{\hat{D}^s}$  in **TABLE 1** is taken. Even if allowed, the rate would be much smaller than the ones for the above decays because of smaller phase space volume. The  $\hat{F}_0^+$  is an iso-singlet counterpart of the  $\hat{F}_I$  mesons. It cannot decay into the  $D_s^+ \pi^0$  as long as the  $I$ -spin is conserved, so that it will decay dominantly through  $I$ -spin non-conserving interactions. In this case, the width of the  $\hat{F}_0^+$  will be extremely narrow (much narrower than the  $\hat{F}_I$  and  $\hat{D}$  mesons). If its mass should be higher (by  $\sim 50$  MeV or more) because of some  $I$ -spin dependent force, it could decay dominantly into the  $DK$  final states (but could be still narrow.) The  $\hat{E}^0$  is an iso-singlet scalar meson with charm  $C = 1$  and strangeness  $S = -1$ , i.e.,  $\hat{E}^0 \sim [cs][\bar{u}\bar{d}]$ . It cannot decay into  $D\bar{K}$  final states unless it is massive enough. If its mass is almost the same as the  $\hat{F}_0^+$ , it cannot decay through strong interactions or electromagnetic interactions [14] as there are no ordinary mesons with  $C = 1$  and  $S = -1$ . If it can be created, therefore, it will have a very long life.

Now we study numerically decays of the  $[cq][\bar{q}\bar{q}]$  mesons. Consider a decay,  $A(\mathbf{p}) \rightarrow B(\mathbf{p}') + \pi(\mathbf{q})$ , as an example. The rate for the decay is given by

$$\Gamma(A \rightarrow B\pi) = \frac{1}{2J_A + 1} \frac{q_c}{8\pi m_A^2} \sum_{spins} |M(A \rightarrow B\pi)|^2, \quad (2)$$

where  $J_A$ ,  $q_c$  and  $M(A \rightarrow B\pi)$  denote the spin of  $A$ , the center-of-mass momentum of the final mesons and the decay amplitude, respectively. To calculate the amplitude, we here use the PCAC (partially conserved axial-vector current) hypothesis and a hard pion approximation in the infinite momentum frame (IMF), i.e.,  $\mathbf{p} \rightarrow \infty$  [15, 16]. In this approximation, the amplitude is evaluated at a slightly unphysical point, i.e.,  $m_\pi^2 \rightarrow 0$ , and is given approximately by the asymptotic matrix element of  $A_\pi$ ,  $\langle B|A_\pi|A \rangle$ , as

$$M(A \rightarrow B\pi) \simeq \left( \frac{m_A^2 - m_B^2}{f_\pi} \right) \langle B|A_\pi|A \rangle, \quad (3)$$

where  $A_\pi$  is the axial counterpart of the  $I$ -spin. *Asymptotic matrix elements* (matrix elements taken between single hadron states with infinite momentum) of  $A_\pi$  can be parameterized by using *asymptotic flavor symmetry* (flavor symmetry of the asymptotic matrix elements). For asymptotic symmetry and its fruitful results, see Ref. [16] and references therein. We here list only the related asymptotic matrix elements [11],

$$\begin{aligned} \langle D_s^+ | A_{\pi-} | \hat{F}_I^{++} \rangle &= \sqrt{2} \langle D_s^+ | A_{\pi^0} | \hat{F}_I^+ \rangle = \langle D_s^+ | A_{\pi^+} | \hat{F}_I^0 \rangle \\ &= -\langle D^0 | A_{\pi-} | \hat{D}^+ \rangle = 2 \langle D^+ | A_{\pi^0} | \hat{D}^+ \rangle \\ &= -2 \langle D^0 | A_{\pi^0} | \hat{D}^0 \rangle = -\langle D^+ | A_{\pi^+} | \hat{D}^0 \rangle. \end{aligned} \quad (4)$$

Inserting Eq.(3) with Eq.(4) into Eq.(2), we can calculate approximate rates for the allowed two-body decays mentioned before. Here we equate the calculated width for the  $\hat{F}_I^+ \rightarrow D_s^+ \pi^0$  decay to the measured one of the new resonance, i.e.,  $\Gamma(\hat{F}_I^+ \rightarrow D_s^+ \pi^0) \sim 10$  MeV, as an example, since we do not find any other decays which can have large rates, and use it as the input data when we estimate the rates for the other decays. [However, the number  $\sim 10$  MeV should not be taken too literally since it is still tentative, i.e., a possibility to take  $\Gamma(\hat{F}_I^+ \rightarrow D_s^+ \pi^0) \sim a \text{ few or several MeV}$  is not excluded.] The results are listed in **TABLE 2**. All the calculated rates of the  $\hat{F}_I$  and  $\hat{D}$  mesons are lying in the region near the input data, so that they will be observed as narrow resonances in the  $D_s^+ \pi$  and  $D\pi$  channels, respectively. As for the  $\hat{D}^s \rightarrow D\eta$  decays, because of  $m_{\hat{D}^s} \simeq m_D + m_\eta$ , it is not clear if they are kinematically allowed. Besides, the decay is sensitive to the  $\eta$ - $\eta'$  mixing scheme which is still model dependent [17]. Therefore, we

**TABLE 2.** Dominant decays of scalar  $[cq][\bar{q}\bar{q}]$  mesons and their estimated widths.  $\Gamma(\hat{F}_I^+ \rightarrow D_s^+ \pi^0) \sim 10$  MeV is used as the input data. The decays into the final states between angular brackets are not allowed kinematically as long as the parent mass values in the parentheses are taken.

Parent (Mass in GeV)	Final State	Width (MeV)
$\hat{F}_I^{++}(2.32)$	$D_s^+ \pi^+$	
$\hat{F}_I^+(2.32)$	$D_s^+ \pi^0$	$\sim 10$
$\hat{F}_I^0(2.32)$	$D_s^+ \pi^-$	
$\hat{D}^+(2.22)$	$D^0 \pi^+$	$\sim 10$
	$D^+ \pi^0$	$\sim 5$
$\hat{D}^0(2.22)$	$D^+ \pi^-$	$\sim 10$
	$D^0 \pi^0$	$\sim 5$
$\hat{D}^s(2.42)$	$D\eta$	–
$\hat{F}_0^+(2.32)$	$< D_s^+ \eta >$	–
	$D_s^+ \pi^0$ ( $I$ -spin viol.)	
$\hat{E}^0(2.32)$	$< D\bar{K} >$	–

need more precise and reliable values of  $m_{\hat{D}^s}$ ,  $\eta$ - $\eta'$  mixing parameters and decay constants in the  $\eta$ - $\eta'$  system to obtain a definite result.

In summary we have studied the decays of the scalar  $[cq][\bar{q}\bar{q}]$  mesons into two pseudoscalar mesons by assigning the new resonance to the  $\hat{F}_I^+$  and assuming the  $I$ -spin conservation. All the allowed decays are not very far from the corresponding thresholds, so that their rates have been expected to saturate approximately their total widths. Therefore, we have used the measured width as the input data. The  $\hat{F}_I$  and  $\hat{D}$  could be observed as narrow resonances such as the new observation. It is very much different from the results in Ref. [7] in which the new resonance was assigned to  $\tilde{D}_{0s}$  [ $\hat{F}_0^+$  in our notation] and all the other  $[c\bar{q}q\bar{q}]$  mesons were predicted to be much broader ( $\sim 100$  MeV or more). To distinguish the present assignment from the other models and to confirm it, therefore, it is important to observe these narrow resonances. Although we have not studied numerically, we can qualitatively expect that the  $\hat{D}^s$  will be much narrower than the  $\hat{F}_I$  and  $\hat{D}$  mesons. The  $\hat{F}_0^+$  decays through  $I$ -spin non-conserving interactions, so that it should be extremely narrow. The  $\hat{E}^0$  will decay through weak interactions if it is created as long as its mass is below the  $\hat{E}^0 \rightarrow D\bar{K}$  threshold.

We have studied, so far, the strong decay properties of a group of the four-quark mesons. If their existence is confirmed, it will be very helpful in understanding of hadronic weak decays of  $K$  and charm mesons. The heavier class of  $[qq][\bar{q}\bar{q}]$  and  $(qq)(\bar{q}\bar{q})$  mesons can play an important role in hadronic weak decays of charm mesons, since the masses of some of the related members are expected to be close to the ones of the parent charm mesons. For example, the expected mass,  $m_{\hat{\sigma}^{**}} \simeq 1.8$  GeV, of the  $\hat{\sigma}^{**} \sim [us][\bar{s}\bar{u}] + [ds][\bar{s}\bar{d}]$  is close to the  $m_{D^0}$  but the one,  $m_{\hat{\sigma}^*} \simeq 1.45$  GeV, of the  $\hat{\sigma}^* \sim [ud][\bar{d}\bar{u}]$  is much lower than the  $m_{D^0}$  as seen in Ref. [9]. Therefore, the former can contribute to the intermediate state of the  $D^0 \rightarrow K^+ K^-$  decay and enhance strongly the decay while the latter can contribute to the  $D^0 \rightarrow \pi^+ \pi^-$  decay but cannot so strongly enhance it. In this way, we can obtain a solution to the long standing puzzle [18],

$$\frac{\Gamma(D^0 \rightarrow K^+ K^-)}{\Gamma(D^0 \rightarrow \pi^+ \pi^-)} \simeq 3, \quad (5)$$

consistently with the other two-body decays of charm mesons [11]. Furthermore, the lighter  $(qq)(\bar{q}\bar{q})$  mesons are useful to understand the violation of the  $|\Delta\mathbf{I}| = 1/2$  rule in  $K \rightarrow \pi\pi$  decays consistently with the  $K_L$ - $K_S$  mass difference, the  $K_L \rightarrow \gamma\gamma$  and the Dalitz decays of  $K_L$  [19].

Confirmation of the existence of four-quark mesons is very much important not only in hadron spectroscopy but also in hadronic weak interactions of  $K$  and charm mesons.

### Acknowledgments

The author would like to thank Professor T. Onogi for providing information of the new resonance, discussions and encouragements, and Professor T. Kunihiro for discussions and encouragements.

- 
- [1] B. Aubert et al., the BABAR Collaboration, Phys. Rev. Lett. **90**, 242001 (2003); D. Besson et al., the CLEO Collaboration, hep-ex/0305017; K. Abe et al., the BELLE Collaboration, hep-ex/0307041.
  - [2] M. A. Nowak, M. Rho and I. Zahed, Phys. Rev. D **48**, 4370 (1993); W. A. Bardeen and C. T. Hill, Phys. Rev. D **49**, 409 (1994).
  - [3] R. N. Cahn and J. D. Jackson, hep-ph/0305012.
  - [4] For example, S. Godfrey, hep-ph/0305122; G. S. Bali, hep-ph/0305209; R. D. Kenway, C. M. Maynard and C. MacNeile, the UKQCD Collaboration, hep-lat/0307001; A. Deandra, G. Nardulli and A. D. Polosa, hep-ph/0307069; Y. -B. Dai, C. -S. Huang, C. Liu and S. L. Zhu, hep-ph/0306274.
  - [5] T. Barnes, F. E. Close, and H. J. Lipkin, hep-ph/0305025.
  - [6] A. P. Szczepaniak, hep-ph/0305060.
  - [7] H.-Y. Chen and W.-S. Hou, hep-ph/0305038.
  - [8] T. E. Browder, S. Pakvasa and A. A. Petrov, hep-ph/0307054.
  - [9] R. L. Jaffe, Phys. Rev. D **15**, 267 (1977); **15**, 281 (1977).
  - [10] S. Hori, Prog. Theor. Phys. **36**, 131 (1966).
  - [11] K. Terasaki and S. Oneda, Phys. Rev. D **38**, 132 (1988); **47**, 199 (1993); K. Terasaki, *ibid* **59**, 114001 (1999).
  - [12] K. Terasaki, Phys. Rev. D **68**, 011501 (2003).
  - [13] K. Terasaki, hep-ph/0309119.
  - [14] H. J. Lipkin, Phys. Lett. **B70**, 113 (1977); M. Suzuki and S. F. Tuan, *ibid* **B133**, 125 (1983).
  - [15] K. Terasaki, S. Oneda and T. Tanuma, Phys. Rev. D **29**, 456 (1984).
  - [16] S. Oneda and K. Terasaki, Prog. Theor. Phys. Suppl. **82**, 1 (1985).
  - [17] T. Feldmann, Int. J. Mod. Phys. A **15**, 159 (2000).
  - [18] Particle Data Group, K. Hagiwara et al, Phys. Rev. D **66**, 1001 (2002).
  - [19] K. Terasaki, Int. J. Mod. Phys. A **16**, 1605 (2001) and references quoted therein.